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14. ABSTRACT

The goal of this project, which lasted from June 1, 2004 to May 31, 2007 was to develop new analysis methods for the modeling of broadband electromagnetic radiation in the time-domain useful for solving electromagnetic interference (EMI) problems. The work was based on a new approach for solving time-domain integral equations (TDIEs) with stability and accuracy, but was soon extended to some other approaches. The results produced by the research done under the auspices of this project lead the way to an EM simulation tool for EMI problems that is accurate, efficient, and stable for the first time ever. The accomplishments of the project can be grouped into two categories: improvements/modifications to the core solution algorithm, and extensions of that algorithm to different physical problems. We will discuss these contributions in the next sections.

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FINAL REPORT
A time domain integral equation approach to electromagnetic interference simulation
Award #N00014-04-1-0564

I. Introduction

The goal of this project, which lasted from June 1, 2004 to May 31, 2007 was to develop new analysis methods for the modeling of broadband electromagnetic radiation in the time-domain useful for solving electromagnetic interference (EMI) problems. The work was based on a new approach for solving time-domain integral equations (TDIEs) with stability and accuracy, but was soon extended to some other approaches. The results produced by the research done under the auspices of this project lead the way to an EM simulation tool for EMI problems that is accurate, efficient, and stable for the first time ever.

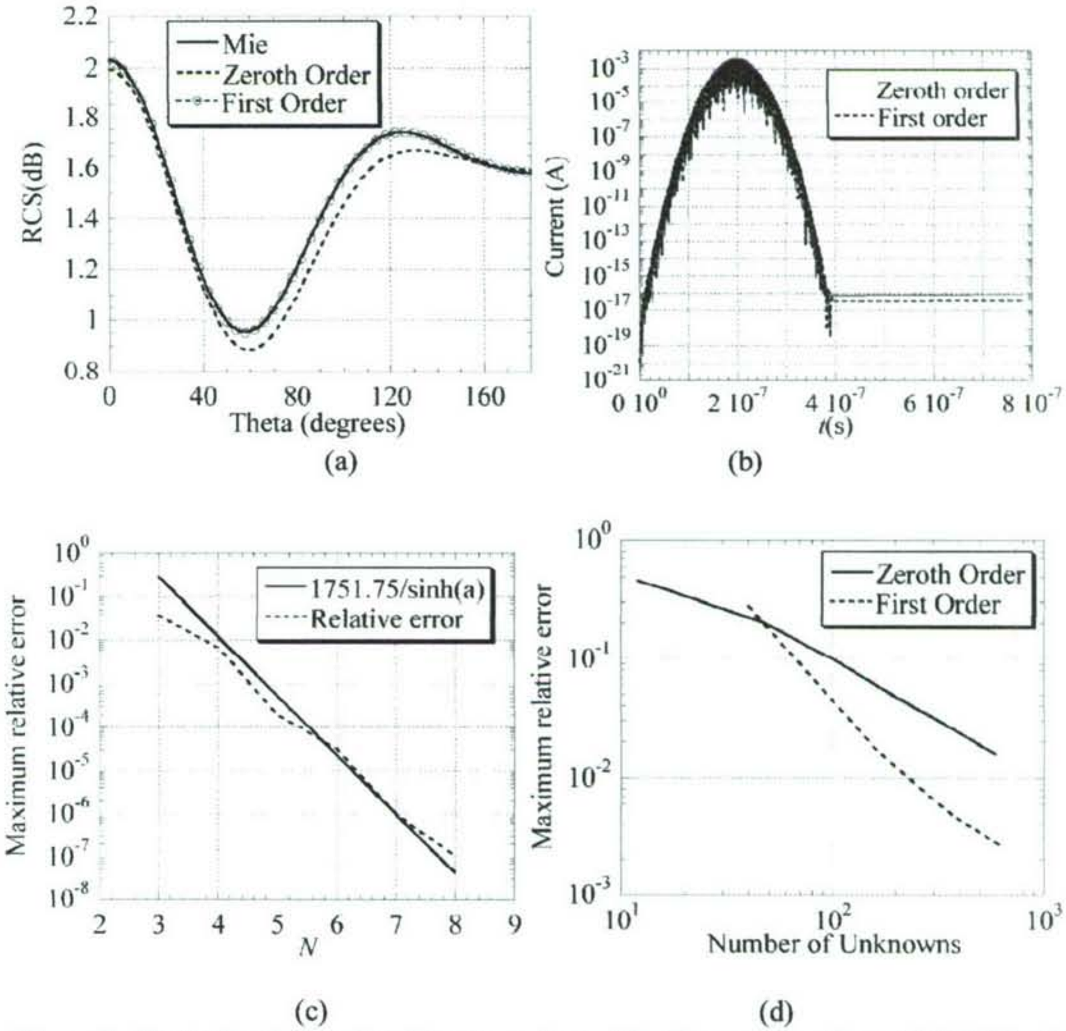
The accomplishments of the project can be grouped into two categories: improvements/modifications to the core solution algorithm, and extensions of that algorithm to different physical problems. We will discuss these contributions in the next sections.

II. Improvements in the core algorithm

Several basic improvements to the algorithm were discovered which improve the algorithms accuracy, stability, or efficiency. The earliest of these improvements (because the work was started before the project became active) came in accuracy through the use of higher-order spatial basis functions. Figure 1 shows the importance of using this technique for the simple problem of scattering from a conducting sphere of one meter diameter. In particular, Subfigures (c) and (d) show that the temporal convergence is exponential with the size of the basis function, and figure (d) shows the influence of higher order spatial convergence: much more accurate results can be obtained with less work. This work is reported in [1].

More work was done on the investigation of stability. In particular, the electric field integral equation (EFIE), which is necessary for the modeling of open conducting structures, has a notorious instability that grows slowly without oscillating. The reasons for this and several solutions for the problem were outlined in [2-4]. In particular, it was shown that the difficulty arises because the EFIE is blind to static, solenoidal currents (which create magnetic fields but not electric fields), and that the problem can be solved by either imposing a condition on the normal magnetic field, or by treating the solenoidal degrees of freedom in the current expansion differently than the others. Figure 2 shows the current on a plate computed both with a stabilized and unstabilized method; clearly, the unstabilized method can easily lead to inaccurate results.

More recent simulations have shown that even with all of these precautions taken, stability can be a problem. Closed thin structures (again, structures that are likely to be important in EMI simulations of naval interest such as airplane wings) can not be computed in a stable fashion with the originally proposed technique. A new method has been discovered in only the past few months that finally renders the method stable in every instance. The new method is based upon the operator calculus; that is, it is based on making finite difference approximations in the Laplace domain. While this new method is not as accurate as the original method (it converges only quadratically while the original method converged exponentially as shown in Figure 1(c)), it is provably stable for every structure and time step size. The original method only worked for very small time steps and (as mentioned above) broke down for thin objects. This can be seen in Figure 3, which shows a very thin almond shaped scatterer and the response of a current near the tip of the almond. Even with all of the tricks discussed above, the original method (BLIF) is unstable, but the new method stays completely stable for the entire simulation. Figure 4 demonstrates the quadratic convergence property, as well as the fact that the method is stable for a host of time step sizes. This work is too new to have been published; a paper has been submitted and is currently in review.



(c) (d)

Figure 1. Scattering from a 1m diameter sphere: (a) radar cross section at 140 MHz, (b) the current at a point on the scatterer, (c) temporal convergence, and (d) spatial convergence.

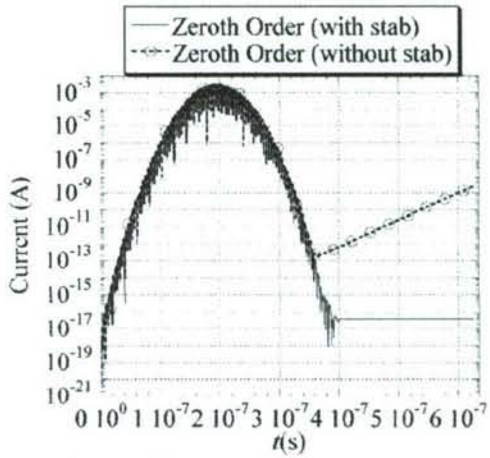
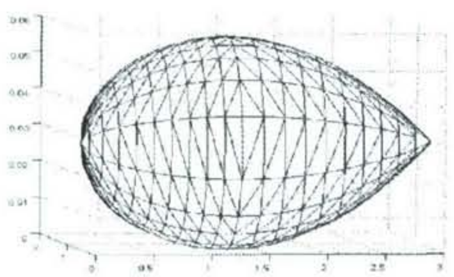
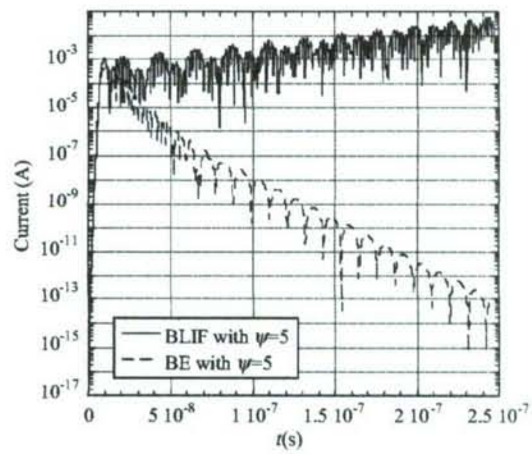


Figure 2. Without the use of a stabilization technique, the current grows exponentially and without bound.





(a) (b)

Figure 3. (a) A very thin almond shaped scatter (not to scale), and (b) the current at a point near the tip computed by two different methods.

The final set of contributions to the core algorithm involves efficiency enhancements. While algorithm speed was not a major concern of the project, it was necessary to ensure that the results we achieved would scale up. The first approach to this problem involved the use of the Nyström method for time domain scattering and is discussed in a set of three papers [5-7]. The Nyström method is an alternative technique for the spatial discretization of TDIEs that operates by directly replacing the integral with a numerical quadrature rule and then enforcing the equation at the quadrature points. Since the Nyström method eschews the integrations needed in an standard Galerkin approach, it can be expected to save memory and time. Unfortunately, after having astounding successes in the simulation of two-dimensional scattering, it was found that instabilities creep into three-dimensional problems using this method. It is possible that this behavior would be corrected by the new Laplace domain approach described in the last paragraph, and this is an important topic for future research.

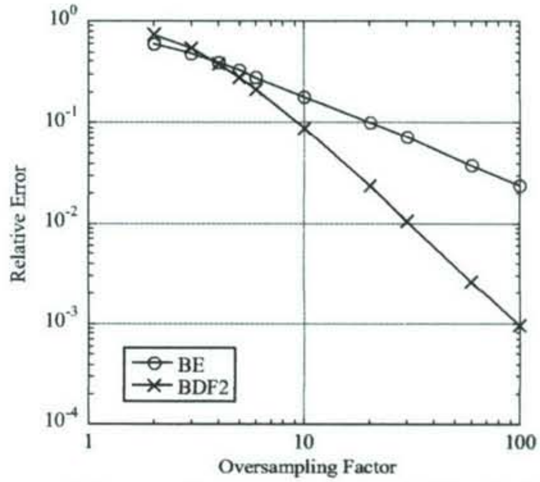


Figure 4. Convergence of the new Laplace domain TDIE solution method. The BE method exhibits linear convergence, and the BDF2 method is quadratic.

Another efficiency improvement, discussed in [8], uses an analytic signal representation to accelerate the solution of TDIEs for narrow band problems. The essential idea behind the approach is that the bandwidth measures the information content of the signal; therefore, the amount of work it takes to run a simulation should be proportional to the bandwidth of the signal being represented rather than the highest frequency contained. Using an analytic signal representation makes this possible, and the resulting algorithm behaves like a combination of the new TDIE scheme and the classical, frequency domain method of moments.

The final efficiency improvement pursued for this work involved the implementation of the adaptive integral method (AIM). Using AIM, it is possible to solve problems involving hundreds of thousands of unknowns. Figure 5 shows the result of using AIM to find the scattering from a sphere discretized with 102,900 unknowns. It took about 2 days to produce this figure, but it would have taken two whole years with a normal approach.

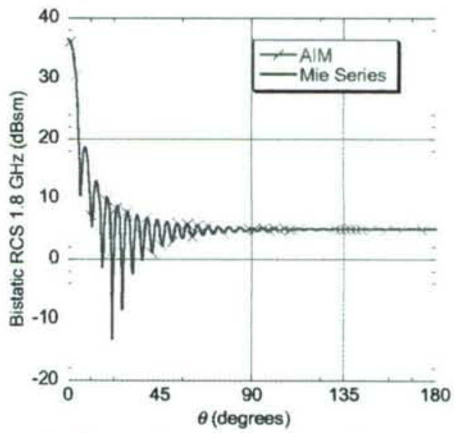


Figure 5. Scattering from a very large sphere.

III. Extensions to Different Physical Problems

In addition to the purely algorithmic extensions described in Section II, the algorithm was also extended to compute the scattering from structures other than pure perfect conductors. The first of these was homogeneous dielectric objects, and the process is outlined in [9]. Figure 6 shows one example of the outcome of this work: The (nearly exact) computation of the radar cross section of a scatterer with surface described by the equation $\mathbf{r}(\theta,\phi) = \sin^2(2\theta)\cos^2(\phi) + 1.5$ and a relative dielectric constant of 6. This dielectric constant is high enough that it made previous time domain codes unstable. Similar results for inhomogeneous dielectrics based on volumetric modeling is also possible, and have been presented at conferences.

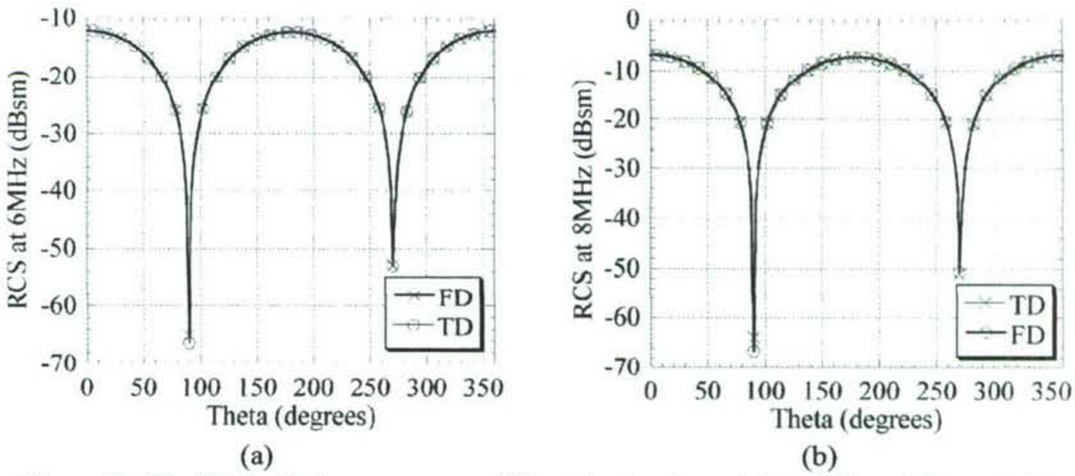


Figure 6. The RCS of a homogeneous dielectric structure at two different frequencies demonstrating the accuracy of the time domain approach.

More important to the simulation of EMI is the ability to simulate wire structures. Because of their high aspect ratio, it can be very difficult to simulate wires accurately. Under the auspices of this project, we created a new method for the high order simulation of wire structures, as well as wire-wire junctions and even wire surface junctions. The work is reported in [10, 11]. Figure 7 shows the result of computing the scattering from a "Y" shaped junction of wires from a normally incident Gaussian plane wave of 60 MHz, 100dB bandwidth. Note again that the method is very accurate. Finally, Figure 8 shows the result of computing the scattering from a sphere (of one-meter diameter) with a half-meter wire attached. This problem involves a surface wire junction. Again, the convergence to the actual solution is very fast. To the knowledge of the PI, these are the first high-order results of this kind in either the time domain or the frequency domain.

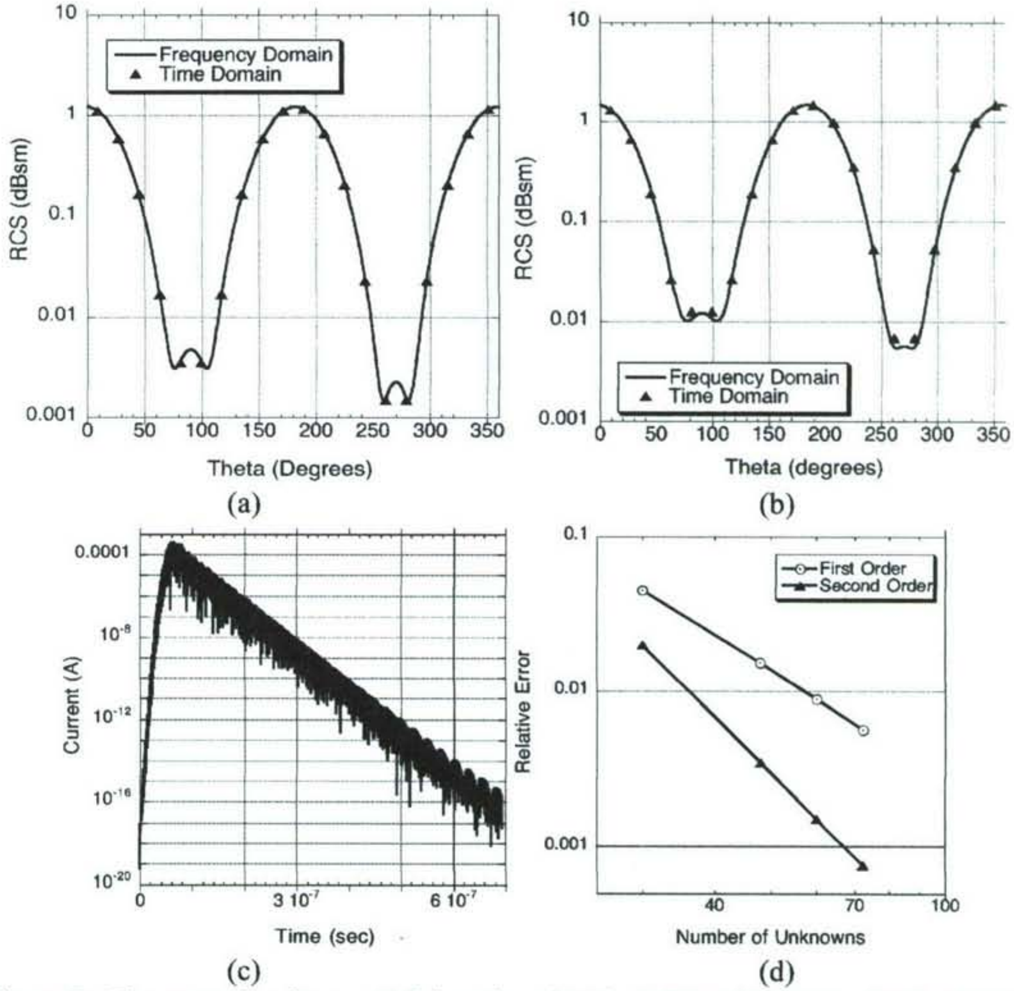


Figure 7. The scattering from a "Y" junction: (a) The RCS at 280 MHz, (b) the RCS at 320 MHz, (c) the current at a point on the long wire, and (d) convergence of the result.

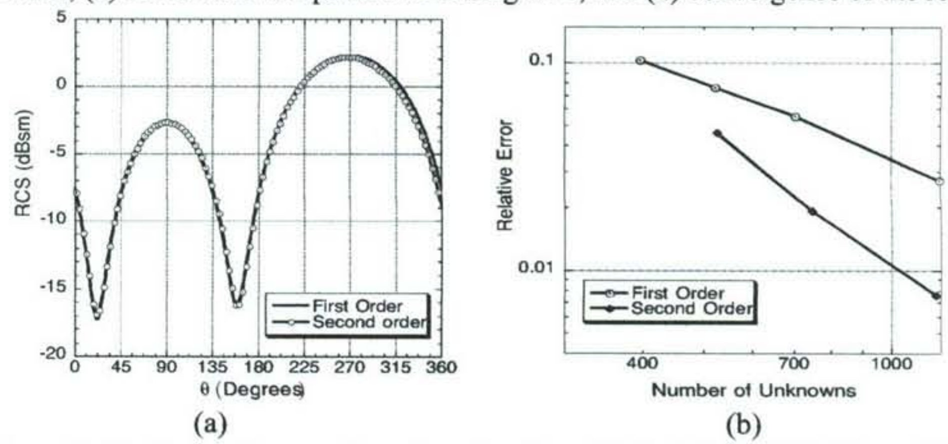


Figure 8. Scattering from a wire-sphere junction: (a) the RCS at 80 MHz, and (b) convergence of the result.

IV. Conclusions

Under this project, new and accurate tools were developed for the analysis of EMI problems. The TDIE method, which when this project began was a mere curiosity, has been developed into a practical tool for EMI analysis, capable of analyzing problems involving conductors, homogeneous dielectrics, and inhomogeneous dielectrics of all configurations. All of these methods exhibit high order convergence (a necessity considering the often small sources of EMI leakage) and can be computed by fast methods.

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